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FUEL-AIR EXPLOSIONS IN A FOG OIL SMOKE ENVIRONMENT

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January 1980

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A fuel-air explosion (FAE) was investigated as a means of neutralizing a smokescreen of fog oil. On three runs a spray of propylene oxide was detonated inside a tactical fog cloud. The FAE did not ignite the fog oil cloud nor was any clearance evinced as judged by visual observation and camera and television recordings.

Transmissometers with lines-of-sight through the clouds operated in the visible and three infrared bands. Immediately after detonation, the transmittance was

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reduced in all four spectral bands. The reduction in transmittance was probably the result of dust lofted by the FAE.

It was concluded that tactical fog oil clouds are very probably too lean to ignite. There was no difficulty in detonating a fuel-air cloud in the covering fog oil cloud.

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I. INTRODUCTION

A. Background

Since the 1973 Arab-Israeli Conflict, the use of smoke in the battlefield has received much attention throughout the world. In particular, the tactical use of smoke greatly reduced the effectiveness of antitank guided missiles against armored assaults during that conflict. With the increased emphasis which the United States has placed on antitank missiles, it is essential to know what countermeasures can be employed against these missiles, and likewise, what actions can be taken to circumvent the countermeasures.

The most plentiful smoke which could currently be employed by either side on the battlefield is fog oil. One question which arises is what techniques can be used to mitigate the effect of smokes (fog oil or other smokes). One mitigation technique currently under investigation by the Ballistic Research Laboratory is the use of fuel-air explosive (FAE) to burn or clear a path through a fog oil smoke cloud.

B. Objectives

The objectives of this project were: (1) determine whether a fuel-air explosion could ignite a fog oil generated smoke cloud, and (2) determine whether the fog oil environment had any effect in creating a fuel-air explosion.

A fuel-air explosion was selected as the ignition source because of certain unique characteristics. The fuel-air cloud has good spatial extent, so it is an area source, not a point source. The energy release is high and it has no smoke of its own. FAE bombs are in inventory and if the technique is successful, they would be available.

II. EQUIPMENT

A. The BRL Small Spray Facility

The spray facility used to generate the fuel-air cloud was designed and tested at the BRL. The principle of operation is shared by many types of sprayers. High pressure gas presses upon a liquid which moves to an on-off valve and flows out a nozzle. The design of the sprayer used in the smoke test is shown in Figure 1. The pressure vessel is an aqualung bottle which holds 0.012 m^3 of propylene oxide (PO). The working flow rate of 2.5×10^{-3} m^3/s (40 gal/min) allows 3 one-second shots. The admission of an inert gas (nitrogen) at a regulated 4140 kPa (600 psi) pressure forces the PO up an eductor tube to a manual on-off valve. Before firing that valve is opened, but the PO is still held back by a DC voltage solenoid valve. The valve outlet pipe is at 1.22 m height and passes through the wall of a blast shield (open on the back side) to a spray nozzle. The nozzle atomizes the fuel

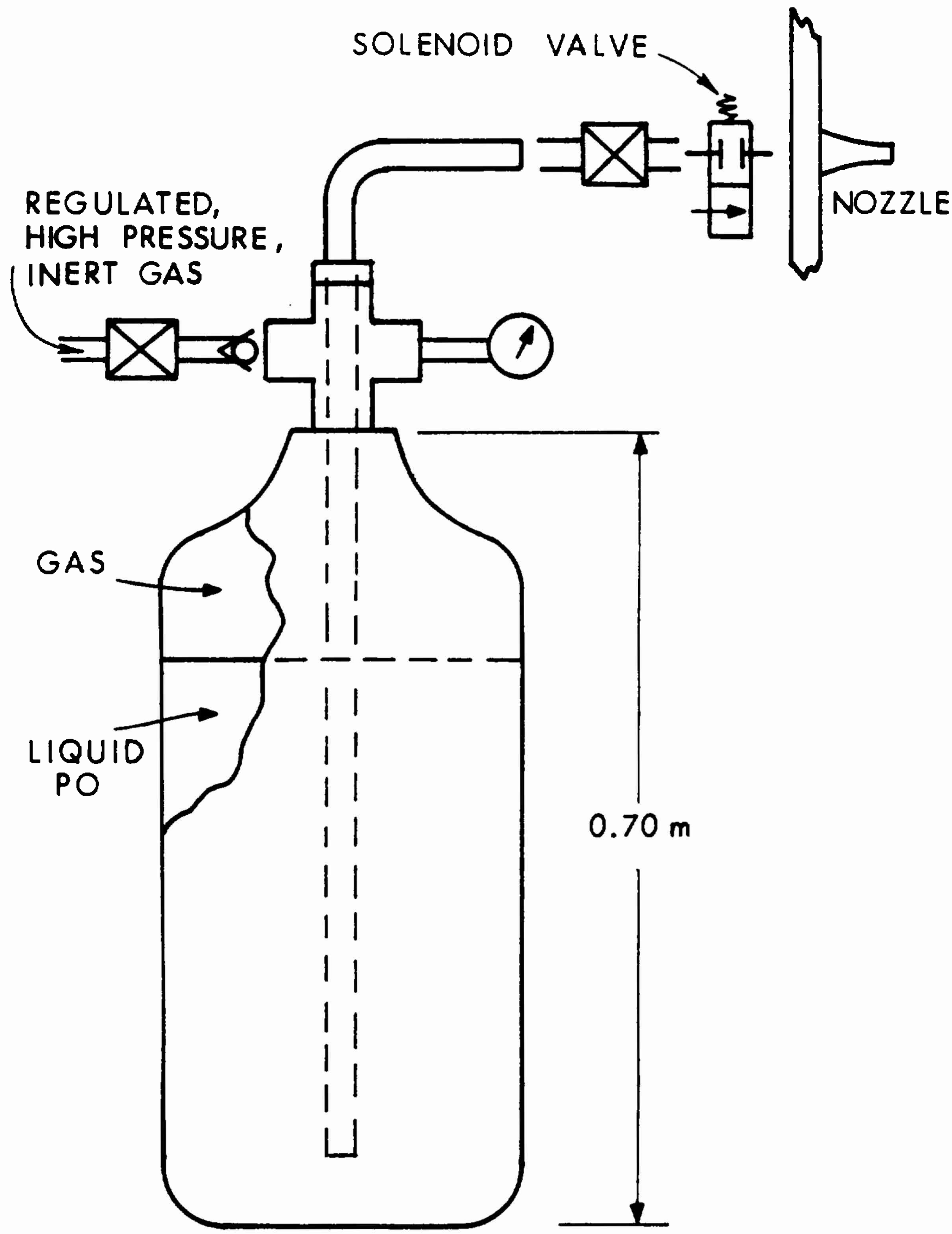

Figure 1. Sketch of small FAE sprayer.

through 24 holes of 0.46 cm diameter and gives a 20° full cone angle. The nozzle is on a swivel ball joint to give aiming compensation for wind. On a still day, the aimpoint is the placement mark for the high explosive needed to initiate the fuel-air explosion. Usually the mark is 2.44 m from the nozzle at a nozzle height (1.22 m).

The order and duration of events is controlled by a programmed sequential controller, Amtron Model 3846. The order of the individual events used are: low speed camera start, sprayer start, high speed camera start, delay, and fire explosive. These events' duration are each reproducible to ±2 ms. The purpose of the delay event (200 - 300 ms) is to allow the solenoid valve time to close, thus, fuel is not injected after the explosive goes and the afterfire is gone quickly.

The weight rate of flow is found by dividing the accumulated spray time from one fill-up into the weight of fuel expended (found by weighing the filled aqualung before and after testing). The weight of fuel sprayed is reported in the RESULTS section. There was no fuel loss to ground contact on the smoke runs.

B. Transmittance Measuring Instrumentation

Four transmissometers were used to characterize the smoke cloud and to determine what effect the FAE event would have on the smoke cloud. By "transmissometer" we are referring to a constant output source of visible or infrared energy and a separated receiver whose signal is continuously recorded. To prevent recording extraneous sources, the field-of-view of the receiver can be limited to the source of interest, or signal processing techniques can be utilized. Then changes in signal strength from the detector can be ascribed to changes in the intervening air path. In the field layout the sources and receivers were 230 m apart. In practice, distinct pairs of source and receiver are not used. Thermal sources emit significant energy across fairly wide spectral bands and receivers can have their spectral sensitivity limited by optical filters. Figure 2 shows the combination of sources and receivers that were actually used. One receiver, focused on a high intensity spot light, obtained measurements in the visible part of the spectrum. This telephotometer contained a photopic filter which resulted in the output of the telephotometer closely matching the response of the human eye from 0.4 to 0.7 micrometers. A second receiver, also focused on the spot light, contained a filter to limit its response to the 0.7 to 1.1 micrometer near infrared region. Two other receivers, focused on a 1000° C blackbody and incorporating appropriate filters, gave measurements in the far infrared region, from 3 to 5 micrometers and 8 to 14 micrometers. More detail on these devices can be found in reference *1*.

[1] *Richard G. Reitz, "An Analysis of Smoke Transmittance Measurements and Techniques", BRL Memo Report No. 2798, November 1977.* (AD #A050370)

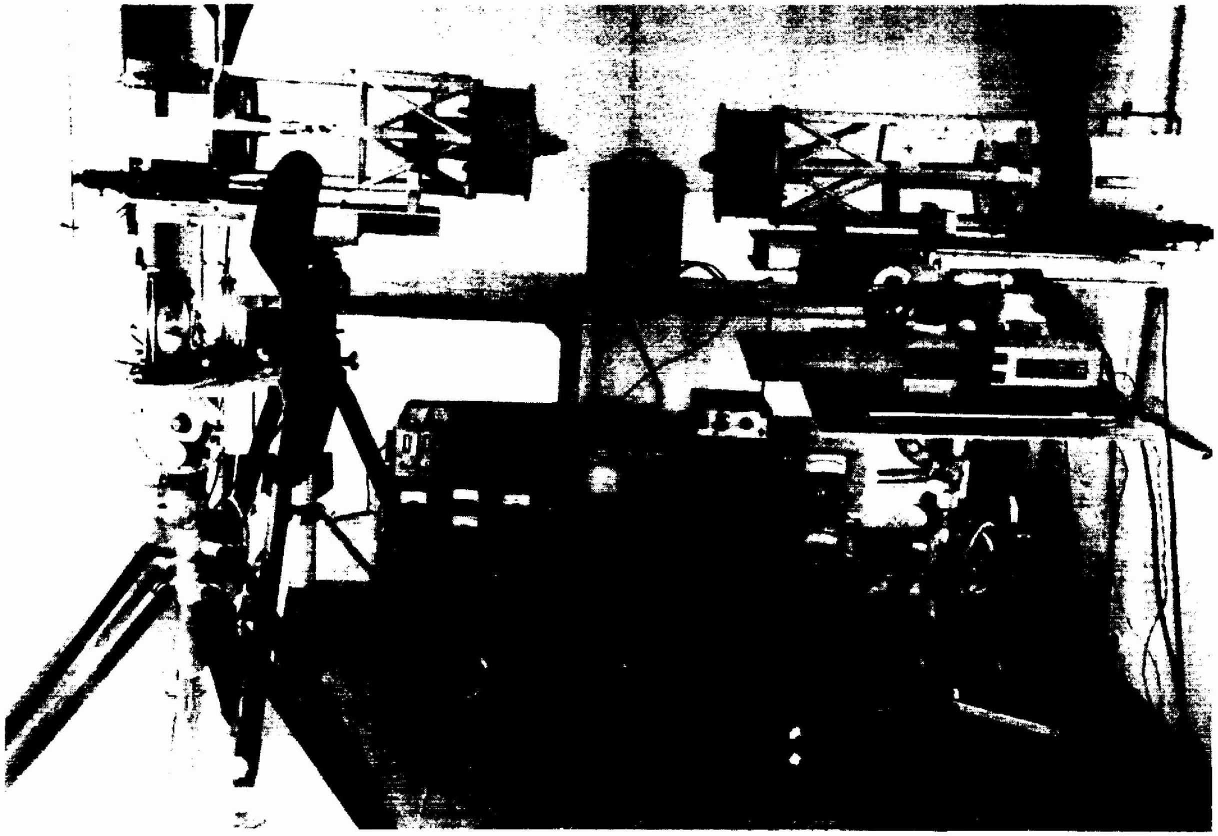

Figure 2. Transmittance measuring instrumentation.

A "clear air" signal level was recorded for each transmissometer with no smoke in the field-of-view of the devices. (The signal strengths were recorded continuously on strip chart recorders.) As the smoke drifted through the fields-of-view of the devices, the signal strengths of the transmissometers varied with the concentration times the path length of the smoke. The chart recordings were analyzed immediately before and after the FAE event to determine what effect the FAE had on the transmittance. The results are reported and discussed later in the report.

C. Smoke Generator

The smoke generator used in the experiment was the U.S. Army M3A3 smoke generator which was initially designed to provide large-area smoke screens. The M3A3 is a gasoline operated pulse jet engine in which fog oil is vaporized by the heat released by combustion gases produced in the engine. The fog oil vapor is then expelled through discharge nozzles to the atmosphere, where it condenses into small droplets to form smoke. More details about the generator can be found in reference 2. Fog oil is ordinary, low-viscosity petroleum oil similar to an SAE 10 motor oil without additives[3]. A photograph of the operating smoke generator is shown in Figure 3.

III. PROCEDURE

A plan view of the test site at Range 8, Spesutie Island is shown in Figure 4. The transmission source trailer and recording trailer were positioned so that the line-of-sight (LOS) was perpendicular to the spray direction. This LOS went through the smaller dimension of the smoke cloud and thus was more sensitive in detecting any post-shot change in smoke cloud transmission. The sprayer was fueled with propylene oxide and connected the day before the test. Near shot time, unprotected personnel (observers) went to roadblocks 120 meters from the sprayer and the sprayer was pressurized. After that step, radios were ordered off the air and the explosive handler armed a bare high explosive charge on a stake prepositioned to be within the fuel-air cloud. When he returned to the sprayer control bunker, 50 meters from the sprayer, the radio net was reopened and smoke generator placement began.

[2] *Operator's and Organizational Maintenance Manual: Generator, Smoke, Mechanical, Pulse Jet, M3A3. Changes 1, 2 , Department of the Army, TM-3-1040-202-12, 12 December 1975.*

[3] *Ronald L. Ohlhaber, B. E. Simonson, "Attenuation of Laser Radiation by HC, FS, WP, and Fog Oil", EATR4100, June 1967.*

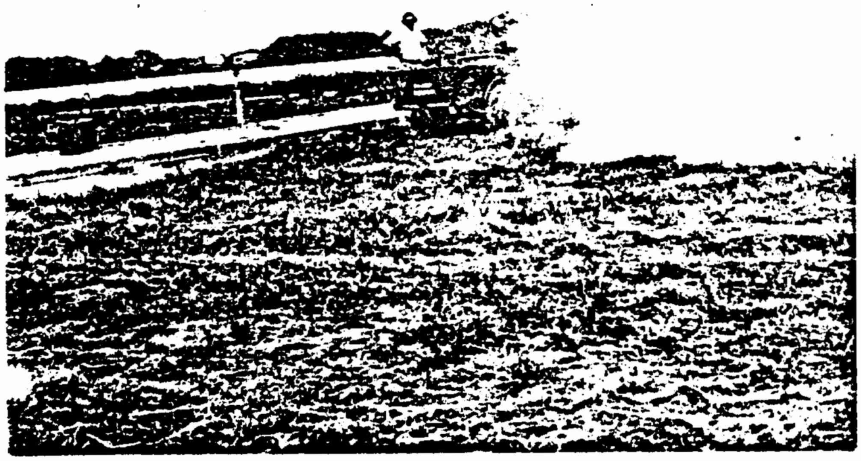

Figure 3. Fog oil generator operating.

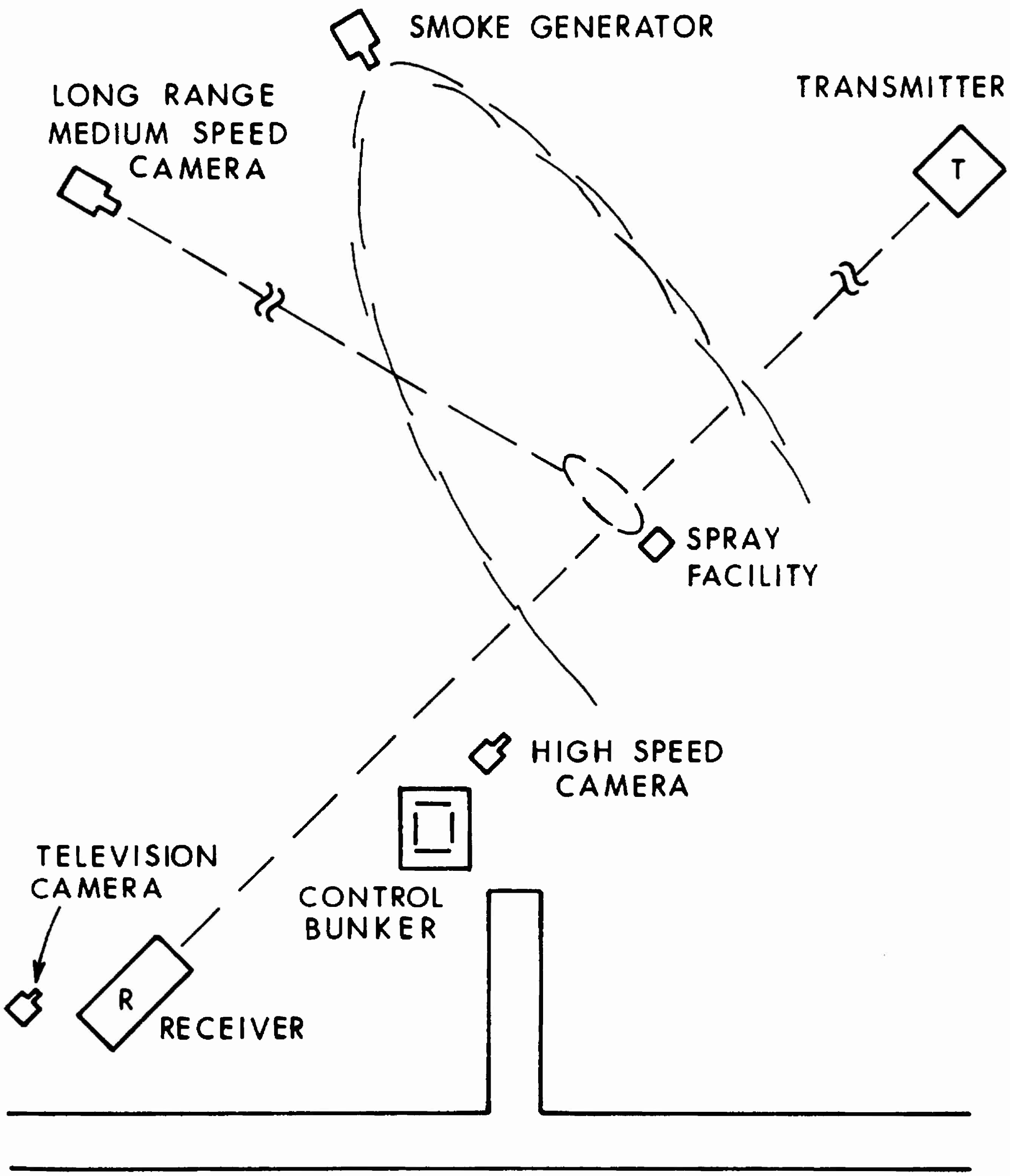

Figure 4. FAE range facility, R-8.

The operating smoke generator was towed by a utility truck to wherever the road block observers said the low wind would drift the smoke cloud over the sprayer, but, importantly, not over the bunker. In addition to direction, the generator was maneuvered until a tactical smoke cloud was judged to exist over the sprayer. This judgement, made by two experienced smoke observers in the transmittance recording trailer, was aided by distinguishing through the smoke a backdrop (2.4 x 1.2 m, yellow and white stripes) that was near the sprayer. In Figure 5 a fog oil cloud is drifting near the blast shield of the small sprayer.

Since the generator's placement could not always be outside the FAE danger zone, an armored personnel carrier (APC) followed along. When the smoke cloud was judged or anticipated to be satisfactorily at the sprayer, the generator was shut down, and personnel entered the APC for shelter. The reason for stopping the generator was for its protection in case a deflagration wave burned back to the fog oil source. Due to the unexpectedly sudden changes in the cloud density, a short countdown to fire was issued from the recording trailer observers to the bunker personnel. The firing delay was therefore about five seconds and a suitable fog oil smoke cloud enclosed the sprayer on each shot.

Recording effects of the FAE on the fog oil cloud continued for several minutes after firing. The longest camera run was five seconds but a television camera and videotape ran several minutes as did the transmission recording equipment. Observers' impressions of effects were also noted. After the first test the head-on camera inside the smoke cloud was not used again. The sprayer could not be seen on film and it was feared that the fog oil would coat the lens. A manually operated camera having a head-on view was used from long range on the second and third tests. In all there were side-on and head-on cameras and observers and a side-on transmission experiment on each shot.

IV. RESULTS

On three runs a fuel-air cloud was detonated in the midst of a fog oil cloud. The fog oil cloud did not ignite nor was any clearance evinced as judged by visual observation, high speed and low speed film, television monitoring and transmission records.

Table I lists data about the fuel-air cloud. Identification of a good detonation was made from high speed film as well as translation of objects near the fuel-air cloud. Table II summarizes the visible and infrared transmission at several times before and after detonation. Plots of the four spectral transmittances are shown for Runs 25 and 27 in Figures 6 and 7 to display some effects of the fuel-air explosion in the fog oil cloud. Due to instrumentation malfunction, transmittance data were not obtained on Run 28.

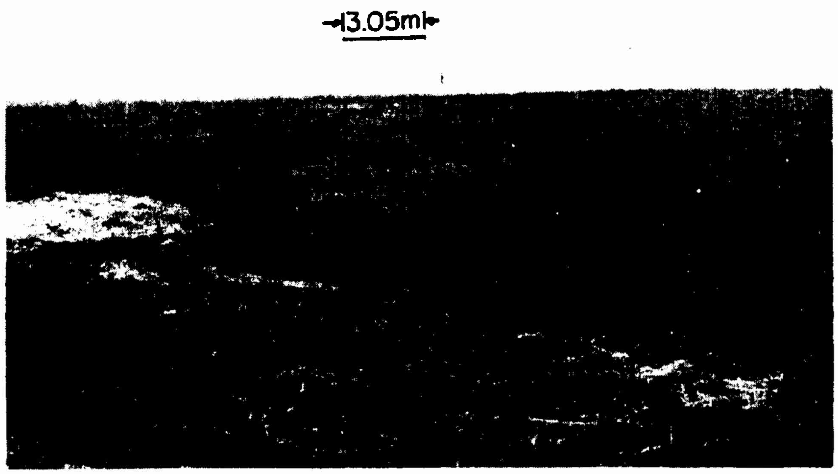

Figure 5. Fog oil cloud near sprayer.

RUN 25
9 JUNE 1978

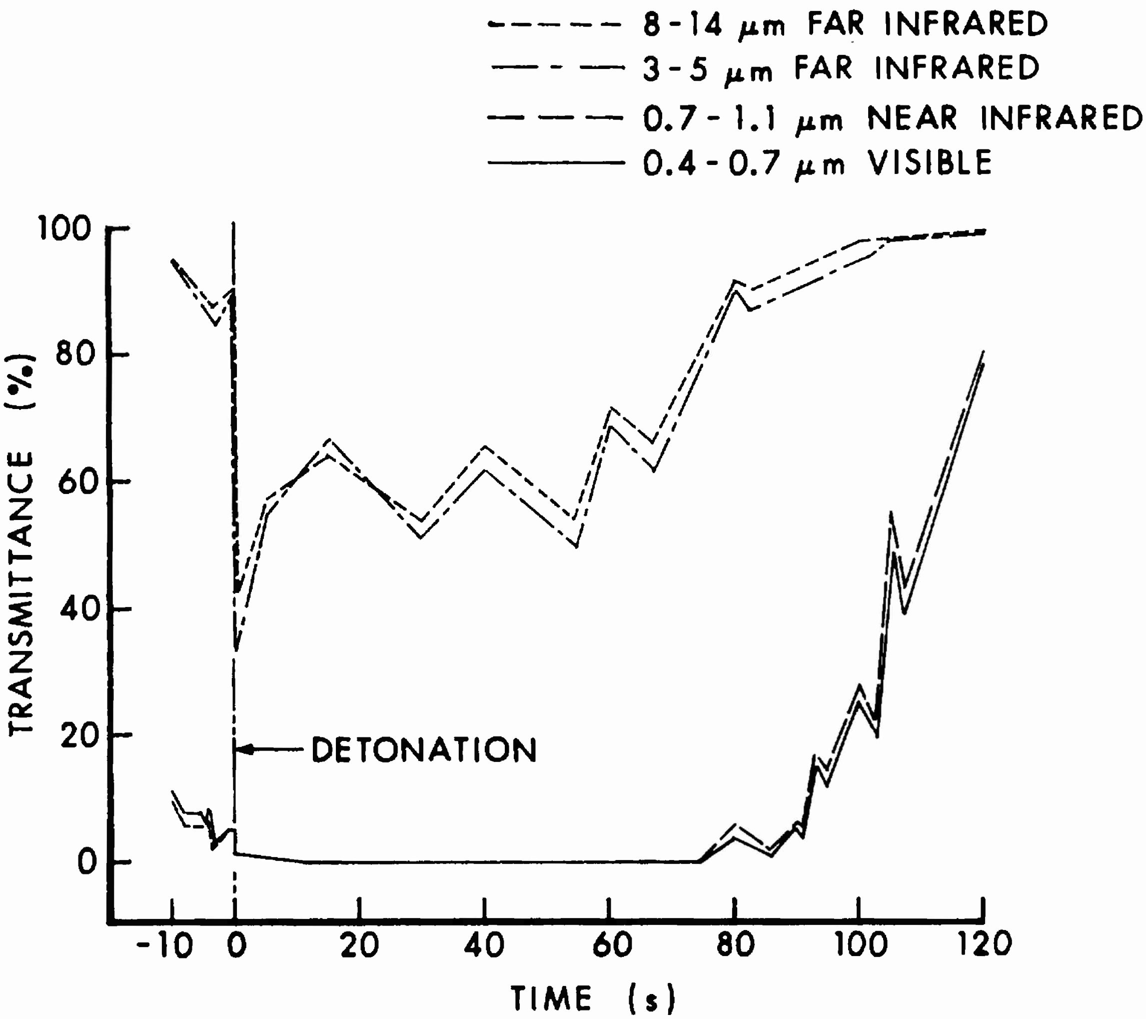

Figure 6. Post-FAE transmittance through fog oil cloud, Run 25.

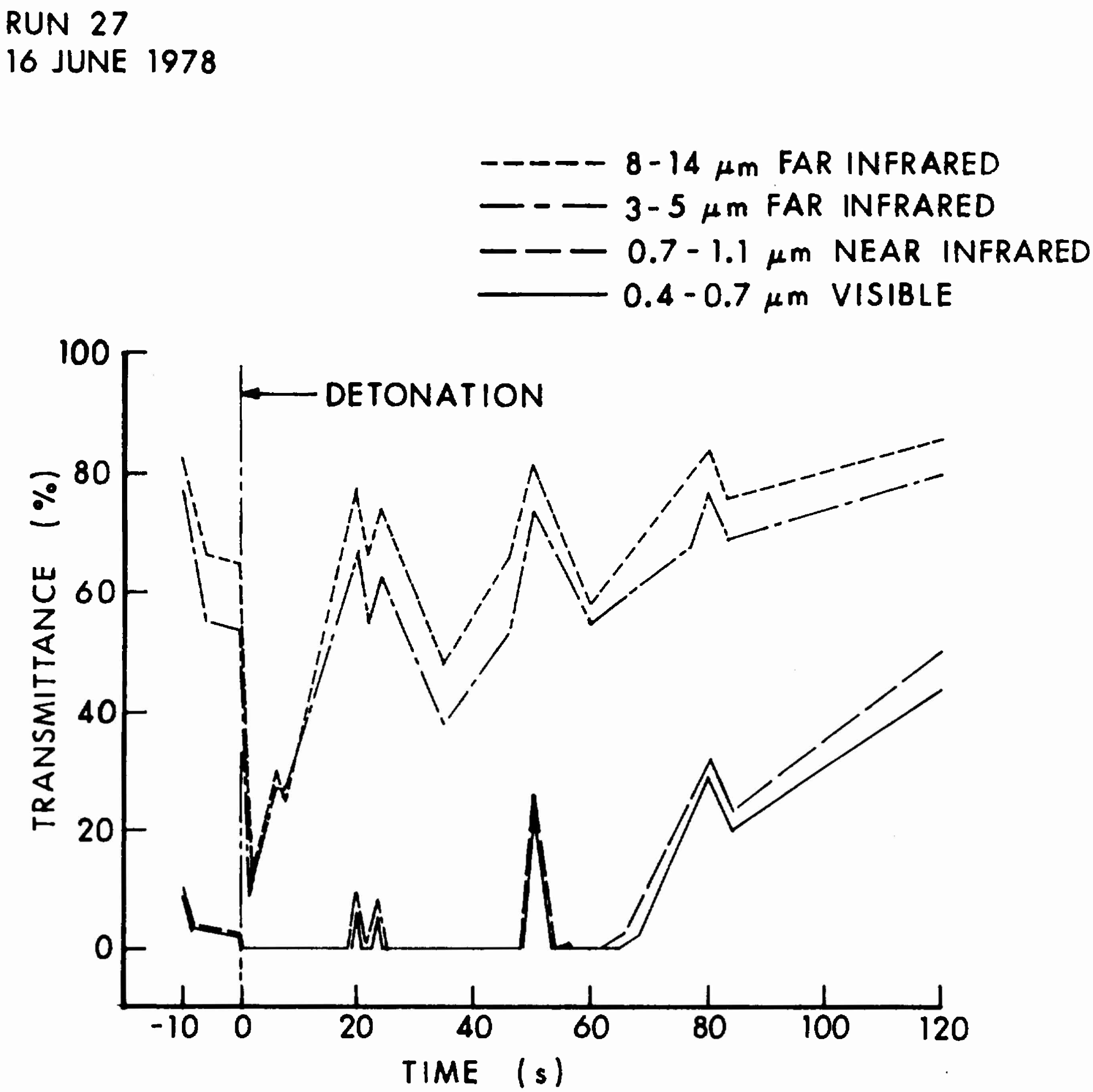

Figure 7. Post-FAE transmittance through fog oil cloud, Run 27.

Table I. Detonation of Fuel-Air Cloud in Fog Oil Cloud

FAE RUN	SPRAY TIME	COMP C-4 INITIATOR	WEIGHT OF PO SPRAYED	DETONATED ?	FOG OIL CLOUD IGNITION ?
	ms	kg	kg		
25	981	0.110	2.2	yes	no
26	---	0.110	ran out of fuel	---	no
27	800	0.055	1.5	yes	no
28	1963	0.110	3.7	yes	no

Table II. FAE Effects on Transmission Through a Fog Oil Cloud

Time s	Percent of Transmission							
	Spectral Band .04 - .07 µm		Spectral band 0.7 - 1.1 µm		Spectral Band 3.0 - 5.0 µm		Spectral Band 8.0 - 14.0 µm	
	Run 25	Run 27	Run 25	Run 27	Run 25	Run 27	Run 25	Run 27
-10	11	10	10	11	95	77	96	83
- 5	8	3	6	4	88	55	89	66
* 0	5	2	5	3	89	54	90	65
1	2	0	2	0	32	9	40	10
5	1	0	1	0	55	28	57	30
10	0	0	0	0	61	34	61	34
30	0	0	0	0	51	49	54	60
60	0	0	0	0	69	55	22	58
90	6	24	7	28	91	71	94	78
120	80	44	81	50	100	80	100	86

* Time 0 is FAE cloud detonation time

V. DISCUSSION OF RESULTS

In all spectral bands, monitoring showed an instant drop in transmission at detonation. The visible and near infrared transmittances were driven to near zero and remained down for two minutes, which is the time for the cloud from the smoke generator to pass. Half the predetonation transmittance was regained in half a minute in the two longer wavelength bands. The jaggedness in the transmission records we assume is due to density changes in the smoke cloud. The major trend of depressed transmission in all spectral bands is, we assume, due to dust lofted by the FAE.

These tests gave no visual or film evidence that the detonating fuel-air cloud ignited the covering fog oil cloud. The reason may be that a tactical fog oil cloud is too thin (fuel lean) to ignite. This suggestion is prompted by fog oil transmittance measurements of Ohlhaber and Simonson[3] which permit concentration to be estimated. From concentration, the fuel-air ratio is obtained, and by comparison with other fuels, it is too lean to ignite. This suggestion is discussed in the APPENDIX.

If leanness is the cause of non-ignition, then FAE cannot be used to ignite tactical fog oil clouds. The possibility that convection can lift the smoke should still be investigated. We saw no clearance at all; however, convection could be scale sensitive. The opposite scale from these tests is a fuel-air cloud large compared to the smoke cloud. In that situation, it is mentioned that detonation of 33 kg of propylene oxide on the edge of a non-combustible, small smoke cloud from burning jet engine fuel JP-5 had no effect on that smoke[4].

VI. CONCLUSIONS

The conclusions reached from this series of tests are: (1) A fuel-air explosion very probably cannot ignite a tactical fog oil cloud; (2) Use of a fuel-air explosion will increase target obscuration in fog oil clouds, in the visible and near-and far-infrared bands due to dust lofted by the FAE; and, (3) A fuel-air cloud will detonate with no difficulty in fog oil clouds.

ACKNOWLEDGEMENT

We would like to thank personnel from the Human Engineering Laboratory at Aberdeen Proving Ground for providing and operating the fog oil generator and insuring that the smoke laid was of realistic density.

[4] *Louis Isaacson, "Physical and Chemical Properties of Fuel/Air Explosives", Geo-Centers, Inc., Newton Upper Falls, Mass. 02164, GC-TR-77-10063, October 1977.*

These men are: Michael Golden, Charles Shoemaker, Mo Singapore, and Charles Spies. We also acknowledge Mr. Kenneth Holbrook of BRL who qualified for bare charge handling in order to support this test. Mr. Charles Kingery provided test guidance and a helpful reading of the manuscript. Dr. Eli Freedman's comments and analysis led to a better estimation of the leanness of the smoke.

APPENDIX

Non-Ignition of Fog Oil Cloud

The reason the fog oil cloud did not ignite may be that is fuel-air ratio was too low to support combustion. This reason was brought into the DISCUSSION OF RESULTS. We pursue this possibility by relating fog oil transmittance measurements to concentration, then to fuel-air ratio. By comparison to other fuels, the ratio we obtain is too lean to ignite.

A. Fog Oil Concentration at Low Transmittance

A smoke agent transmission study by Ohlbaber and Simonson[1] characterizes the obscuring power of a smoke by a number called "total obscuring power" (TOP) which is the reciprocal of concentration C and path length b for 1.25 percent transmittance.

$$\mathrm{TOP} = \frac{1}{Cb}$$

For transmission of white light through fog oil, TOP = 666 m^2/kg and using their path length of 1.87 m, the concentration is $C = 8.03 \times 10^{-4}$ kg/m^3.

The physical property of the smoke that allows us to find its concentration at any transmittance is the absorptivity, a. The absorptivity of a light extinquishing substance is related to the transmissivity, T, by the equation

$$T = 10^{-abC}$$

where b is the path length through the medium and C is the concentration of the substance. By using the previous data the absorptance (the measured value of absorptivity) of the fog oil is

$$\log (0.0125) = -a\ (1.87\mathrm{m})\ (8.03 \times 10^{-4}\ \mathrm{kg/m^3})$$

$$a = 1267\ \mathrm{m^3 air/kg\ liquid/m\ path\ length}$$

B. Path Length Through the Fog Oil Cloud

Run 25 was a "good" one; that is the experienced observers declared the smoke to be of useful hiding power in a real military situation. Table II shows that at the place and instant the FAE was initiated the transmittance was 0.05 in the visible. The path length is not known because we did not have an aerial camera looking down on the fog oil cloud. However, some estimates are available. The source-receiver separation was 230 m and the bunker-sprayer separation was 48.8 m. Care was taken not to cover the control bunker with the fog oil cloud, so with symmetry the path length would be 2 x 50 m. Entering various estimates of the path length into Table A1 the concentration is found from $\log (0.05) = -1267\ \frac{\mathrm{m^3/kg}}{\mathrm{m}}\ (b(\mathrm{m}))\ C(\mathrm{kg/m^3})$.

1Ronald L. Ohlhaber and Bernard E. Simonson, "Attenuaton of Laser Radiation by HC, FS, WP, and Fog Oil Smokes", Edgewood Arsenal TR4100, June 1967.

Table A1. Estimate of Smoke Concentration, Run 25

Comment	Source-Receiver Distance	Path Length b (m)	Concentration c (kg/m^3)	Fuel-Air Ratio (F/A)v
Did not occur	Full of Smoke	230	4.45×10^{-6}	7.53×10^{-7}
Possible	Half Full	115	8.91×10^{-6}	1.53×10^{-6}
Likely	Quarter Full	57.5	1.78×10^{-5}	3.01×10^{-6}
Possible	Twice bunker-sprayer	97.6	1.05×10^{-5}	1.78×10^{-6}

The last column of Table A1 is filled in by the method explained in the next part, C.

C. Conversion of Concentration to Fuel-Air Ratio

Fuel-air ratios refer to vapor phases of fuel to air. The vapor equivalent VE in m^3 of one m^3 of liquid is[2]:

$$(\mathrm{m}^3)\ \mathrm{VE} = 830\ \frac{\mathrm{SpGv}}{\mathrm{VD}}\ (\mathrm{m}^3),$$

where

VD = MWfuel/MWair
MW = molecular weight
SpGv = specific gravity

Fog oil is SAE 10 motor oil without additives[1]. SAE 40 motor oil is more viscous but the properties are not enough different to affect the calculation of vapor equivalence.

SAE 40 Oil SpGv = 0.857

$$\mathrm{VD} \simeq 142/29 \approx 4.90$$

i.e., vaporized motor oil is nearly five times heavier than air on a volume basis.

SAE 40 VE = 145 m^3/m^3

i.e., a unit volume of liquid motor oil occupies 145 unit volumes as a vapor. From Table A1 a likely concentration of the fog oil prior to FAE initiation was $C = 1.78 \times 10^{-5}$ kg liquid/m^3 air or as a volume of liquid oil,

[2] *Fire Protection Handbook, National Fire Protection Association, Boston, 13th Edition, 1969.*

$$C = (1.78 \times 10^{-5} \text{ kg liquid/m}^3 \text{ air})/857 \text{ kg liquid/m}^3$$

$$C = 2.07 \times 10^{-8} \text{m}^3 \text{ liquid/m}^3 \text{ air}$$

The vapor equivalent of this concentration of fog oil particles is

$$C = (145 \text{ m}^3 \text{ vapor/m}^3 \text{ liquid}) \; (2.07 \times 10^{-8} \text{ m}^3\text{liquid/m}^3\text{air})$$

$$C = 3.01 \times 10^{-6} \text{ m}^3\text{vapor/m}^3\text{air}$$

But the concentration expressed as fuel vapor to air by volume is the fuel-air ratio by volume,

$$C \text{ (Vapor)} \equiv (F/A)v$$

$$(F/A)v = 3 \times 10^{-6} \sim 10^{-6}$$

So the fog oil cloud on Run 25 just prior to and near the FAE initiation point had a fuel-air ratio around 10^{-6}.

D. Comparison of Fuel-Air Ratios

The lower flammable limit is the least fuel-air mixture that will burn. The Table A2 shows for several fuels that the fuel-air ratio by volume is one percent.

Table A2. Lower Flammable Limit Per Cent Vapor by Volume[2]

Fuel	(F/A)v (Lean)
Acetone	2.67
Benzene	1.32
Ethyl Alcohol	3.48
Gasoline	1.07
High-Solvency Petroleum Naptha	1.00

This table is sufficient to indicate that the least amount of vaporized fuel in air that will give a combustible mixture has a fuel-air ratio that is $(F/A)_v \sim 10^{-2}$ for flammable substances.

E. Discussion

The smoke cloud is composed of ultra-small droplets of fog oil and the fuel-air explosion supplies the heat to vaporize these droplets and raise the vapor to the flash point. If combustion starts, a flame front would begin propagating through the smoke cloud. The fuel-air explosion supplies ample heat since the heat of combustion of propylene oxide is 7.6 kcal/gm and the lean detonation mixture of PO

is 68 gm liquid/m^3 air, which gives the FAE an energy release greater than 500 kcal/m^3 air. The heat of vaporization of petroleum products is only 200 cal/gm and with a smoke concentration (Table A1) of 0.002 gm/m^3, just 0.4 cal/m^3 air is all that is required to vaporize the fog oil droplets. Thus in section C we can leapfrog from liquid concentration, which characterizes the smoke cloud, to vapor concentration of fog oil, which exists throughout the fuel-air explosion.

Since the fog oil was completely vaporized in the FAE and it had a fuel-air ratio four orders of magnitude less than required, it could not have burnt. Neither could the fog oil, regarded as a vaporous fuel-air mixture in the FAE region, have exploded because the lean deflagration limit of fuels is always smaller than the lean explosive limit. A further obstacle is that most fuels are not detonable in an unenclosed state and fog oil has not been shown to be an exception. However, the fog oil cloud is a suspension of 1-10 μm diameter organic particles and it is of interest to compare the Run 25 concentration to explosive concentrations of dust. Organic dusts' lean explosive concentrations in chambers are given in Reference 2 and are typically no smaller than 0.05 kg/m^3 (0.05 oz/ft^3). The concentration of fog oil from Table A1 was at most 1.78×10^{-5} kg/m^3 air. So the fog oil cloud was 2500 times below the lean explosive limit of dusts.

Presumably a flammable or too rich mixture exists in some region close to the smoke generator. But across the field that the fog oil smoke is hiding there is no flammable region of fog oil. Greater heat release from larger explosions or hotter burning igniters such as aluminum powder will not ignite the fog oil cloud.

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